Generation and cross-validation of large-area forest stem volume maps for northeast and southeast China using ERS-1/2 tandem coherence

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Abstract: The creation of large-area forest stem volume maps of Northeast (1,5 Million km2) and Southeast China (3 Million km2), based on ERS-1/2 tandem coherence data, was the aim of the FOREST DRAGON 1 project. The accuracy assessment of the map products is one of the objectives of the ongoing FOREST DRAGON 2 project. The ERS-1/2 tandem datasets consisted of 223 and 407 image pairs for Northeast and Southeast China respectively and were acquired in all seasons between 1995 and 1998. ERS-1/2 tandem coherence has been shown to provide accurate estimates of forest stem volume but is also known to depend strongly on the meteorological and environmental conditions at image acquisition. Existing algorithms for large-area mapping have so far not been able to classify forest stem volume based on a multi-seasonal dataset. For this reason a new classification approach, based on synergy between the optical remote sensing product MODIS Vegetation Continuous Fields and ERS-1/2 tandem coherence has been developed for automatic and seasonal-adaptive retrieval of forest stem volume. The procedure integrates the semi-empirical Interferometric Water Cloud Model and discriminates between four stem volume classes (0-20, 20-50, 50-80 and >80 m3/ha). For the evaluation of the large-area forest stem volume maps, a special cross-comparison design based on other Earth Observation products had to be developed due to the unavailability of large-scale datasets of in-situ measurements. A multi-scale comparative assessment design with existing land cover products such as GLC2000, GlobCover and MODIS VCF product has been applied. The sampling design, based on the FAO FRA2010 Sample Design and the Degree Confluence Project, uses a 1 degree sampling grid with 10 x 10 km sample plots and is completely transferable to other large-area investigation areas. A reasonable agreement above 70% between the forest stem volume map and the land cover datasets in terms of forest/ non-forest could be achieved.

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Generation and cross-comparison of large-area forest stem volume maps for Northeast and Southeast China, using ERS-1/2 tandem coherence

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ABSTRACT

The creation of large-area forest stem volume maps of Northeast (~1,5 Million km²) and Southeast China (~3 Million km²), based on ERS-1/2 tandem coherence data, was the aim of the FOREST DRAGON 1 project. The accuracy assessment of the map products is one of the objectives of the ongoing FOREST DRAGON 2 project. The ERS-1/2 tandem datasets consisted of 223 and 407 image pairs for Northeast and Southeast China respectively and were acquired in all seasons between 1995 and 1998. ERS-1/2 tandem coherence has been shown to provide accurate estimates of forest stem volume but is also known to depend strongly on the meteorological and environmental conditions at image acquisition. Existing algorithms for large-area mapping have so far not been able to classify forest stem volume based on a multi-seasonal dataset. For this reason a new classification approach, based on synergy between the optical remote sensing product MODIS Vegetation Continuous Fields and ERS-1/2 tandem coherence has been developed for automatic and seasonal-adaptive retrieval of forest stem volume. The procedure integrates the semi-empirical Interferometric Water Cloud Model and discriminates between four stem volume classes (0-20, 20-50, 50-80 and >80 m³/ha). For the evaluation of the large-area forest stem volume maps, a special cross-comparison design based on other Earth Observation products had to be developed due to the unavailability of large-scale datasets of in-situ measurements. A multi-scale comparative assessment design with existing land cover products such as GLC2000, GlobCover and MODIS VCF product has been applied. The sampling design, based on the FAO *FRA2010 Sample Design* and the *Degree Confluence Project*, uses a 1 degree sampling grid with 10 x 10 km sample plots and is completely transferable to other large-area investigation areas. A reasonable agreement above 70% between the forest stem volume map and the land cover datasets in terms of forest/ non-forest could be achieved.

Keywords: Stem Volume, ERS-1/2 Coherence, Cross-Comparison, China

1. INTRODUCTION

The forests of Northeast China and Southeast China, which represent one of the most important wood supplies in China, have been undergoing constant pressure for several decades. The existing forest resources are not considered adequate for the needs of the Chinese economy and livelihood of the Chinese people. According to [1] the main problems are low total volume, low quality and sluggish growth of both, naturally growing forests and plantations. The existing statistics about forest area, type and quality in China differ significantly [2] and indicate a need to monitor the forests status and their development on a regular basis. This represents the background to the activities undertaken within the FOREST DRAGON 1 project, a subproject of the ESA-MOST Dragon Programme. The aim was the creation of large scale forest stem volume maps for Northeast and Southeast China, based on ERS-1/2 tandem interferometric SAR coherence. The accuracy assessment of the map products is one of the primary objectives of the ongoing FOREST DRAGON 2 project.

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Radar remote sensing has been shown to allow the retrieval of forest area extent and forest resources in the form of growing stock volume. Several studies have shown that ERS-1/2 tandem coherence can be used to assess forest wood resources [3,4,5] with reasonable accuracy under 'good' (i.e. stable frozen) imaging conditions. However, the achievable retrieval accuracy is related to the strong sensitivity of coherence to meteorological and environmental conditions. In turn this variability makes forest stem volume mapping strongly dependent on forest inventory data in order to correctly tune the models relating coherence to growing stock volume.

Large area applications of interferometric SAR techniques for forest mapping are scarce. At the moment only existing large-area forest cover map has been produced within the 'SAR Imaging for Boreal Ecology and Radar Interferometry Applications' SIBERIA project [6,7]. The result of this project was a forest cover map of a ~ 1 Million km^2 large area in Central Siberia, which discriminates four stem volume classes (0-20, 20-50, 50-80 and > 80 m^3/ha). However, the application of the SIBERIA algorithm has narrow confines since it has been developed for ERS-1/2 tandem coherence data, acquired only in fall, using a simple empirical model.

One of the goals of the Forest DRAGON 1 project was to produce a forest stem volume map based on ERS tandem data. However, due to the lack of full coverage of multitemporal data that is acquired under good conditions, the production of a SIBERIA type of map (stem volume map), discriminating at least some low stem volume classes, was considered to be more realistic. The given ERS-1/2 tandem datasets consisted of 223 and 407 image pairs for Northeast and Southeast China respectively and were acquired under a wide range of meteorological conditions and perpendicular baselines (0 – 400 m) in all seasons between 1995 and 1998. The dataset spanning different seasons and baselines length showed the limits of the SIBERIA approach [9]. For this reason a new retrieval algorithm was developed to be able to cope with multi-seasonal and multi-baseline data in an automatic retrieval procedure.

The evaluation of the produced large area stem volume maps is mandatory for presenting the value of the products. A special cross-comparison design based on other EO products had to be developed due to the unavailability of large-scale datasets of in-situ measurements.

After the description of the study area and the ground-truth data used for this study (Sec. 2), the development and the production of a SIBERIA type of map for Northeast and Southeast China is presented (Sec. 3). The evaluation of the produced stem volume maps in terms of forest/ non-forest information using a cross-comparison scheme (Sec. 4) is followed by a summarising conclusion.

2. STUDY AREA AND GROUND DATA

The study areas cover the northeast and the southeast part of China. Though, only for Northeast China inventory data was available. The Chinese academy of Forestry provided inventory data for three test sites located in the Greater (53°8' N, 123°4' E) and Lesser Hinggan (47°10' N, 128°53' E) mountains and the Changbai area (42°60' N, 128°10' E) which represent the main forested areas in Northeast China. The data comprised information about stem volume and height for each stand and was provided together with stand-wise measurements of ERS-1/2 tandem coherence and backscatter. Since only three ERS-1/2 tandem pairs, all acquired under frozen winter conditions, were available for the three northern Chinese test sites, the methodological development was extended to five compartments of three forest enterprises located in Central Siberia: Bolshe-Murtinsky (57°5' N, 92°55' E), Chunsky (57°45' N, 96°43' E) and Primorsky (55°46' N, 102°30' E).

3. CREATION OF THE LARGE-AREA FOREST STEM VOLUME MAPS

3.1 Interferometric processing

The interferometric processing was done on a frame basis (100 km x 100 km). It consisted of co-registration at sub-pixel level, multi-looking (1x5 for the Siberian dataset, 2x10 for the Chinese dataset), common-band filtering and adaptive coherence estimation using window sizes between 3x3 and 9x9 pixels. For the common-band filtering of the Southeast China dataset, SRTM-3 DEM data was included to consider effects in sloping areas. All coherence and backscatter images were geocoded using SRTM-3 DEM data [10]. During geocoding, the Siberia and Chinese images were resampled to a pixel size of 25x25 m^2 and 50x50 m^2 respectively. A more detailed description of the ERS-1/2 tandem coherence mosaic covering Northeast China is described in [11]. During the geocoding, maps of slope angle, layover/shadow, pixel normalization and local incidence angle were produced. These were used in the interpretation of the coherence and the backscatter measurements.

3.2 Methodology

The semi-empirical model used in this study to retrieve stem volume from coherence was the Interferometric Water Cloud Model (IWCM) [13]. This model has been shown to be capable of describing the relationship between coherence and stem volume under a wide range of environmental and meteorological imaging conditions [3,4]. The model describes the coherence of a forest as a sum of a ground and a vegetation contribution. The IWCM includes five unknowns that should be determined via model training based on forest inventory data. The determination of the model unknowns so far has relied on the availability of forest inventory data [3,4]. In theory the high spatial variability of coherence requires a very high density of training sites, in order to be able to capture these variations and obtain a spatially consistent modeled coherence. For Northeast and Southeast China this was not the case, hence a model training method independent from inventory data was developed. Herefore, the MODIS Vegetation Continuous Field (VCF) tree cover product [8] was included into the model training phase. The VCF product provides global sub-pixel estimates of tree cover at 500 m pixel size. A detailed description of the methodology is given in [12].

Since the ERS datasets that are available for Northeast and Southeast China comprised a considerable fraction of images acquired under unstable conditions, no discrimination of high stem volume classes was possible when aiming at obtaining consistent forest stem volume maps. Therefore the accuracy of a SIBERIA-type of class discrimination with four stem volume classes (0-20, 20-50, 50-80 and >80 m^3/ha) was used. The classification was carried out by applying simple thresholds to the stem volume derived by inverting the training model [12]. The clear relationship between the ERS-1/2 tandem coherence and the VCF product suggested that several model parameters can be derived from masking the coherence image for low and high VCF values.

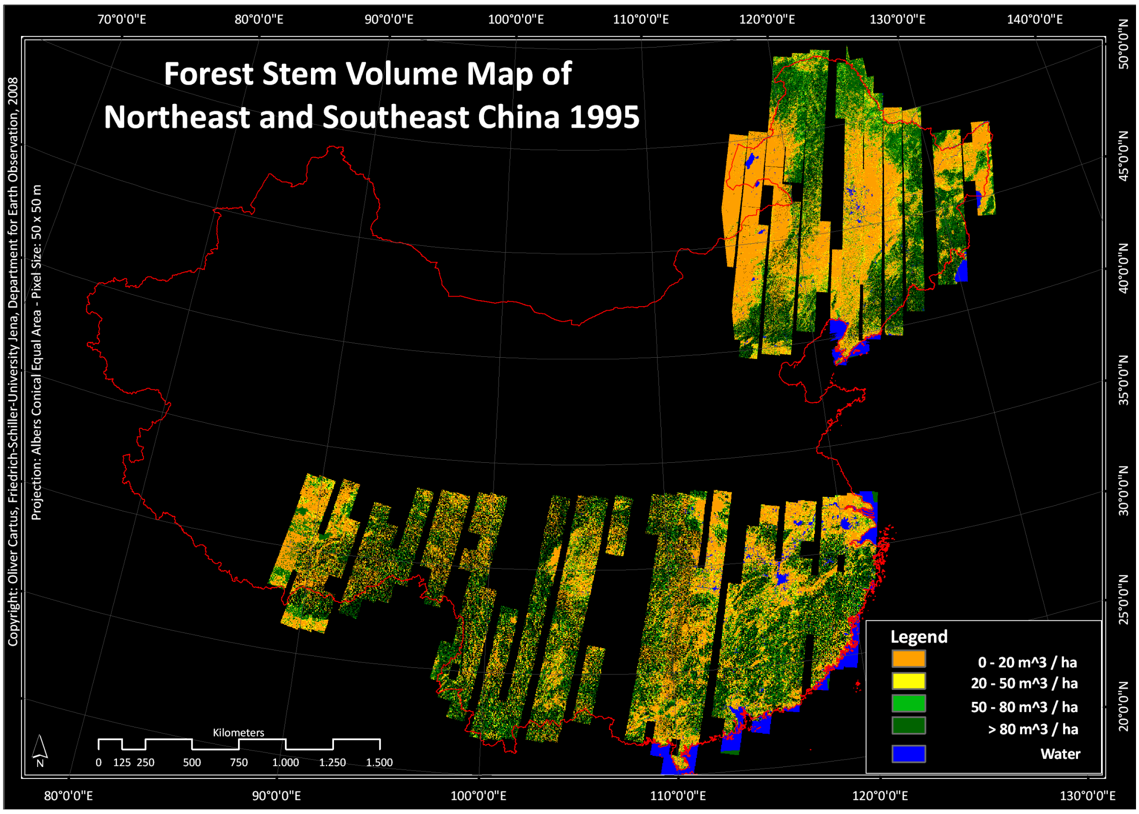

Fig. 1. Forest stem volume map of Northeast and Southeast China obtained from ERS-1/2 tandem coherence data for the years 1995 – 1998.

3.3 Results

Figure 1 shows the forest stem volume (FSV) map of Northeast and Southeast china obtained from the ERS-1/2 tandem coherence. Areas for which the stem volume has been retrieved, which are based on stable frozen winter conditions show superior information content because consistent model parameters estimations could have been acquired. For images acquired under unstable conditions (e.g. rainy conditions), the model parameters strongly varied. Nonetheless, the automated procedure was able to obtain a reasonable description of the dependence of coherence upon the forest growing stock volume. The produced forest stem volume maps, show homogeneous and consistent estimates. The maps do not show the stripping effects due to seasonal conditions that are clearly visible in the coherence data.

4. CROSS-COMPARISON

Due to the unavailability of large-scale datasets of in-situ measurements, the validation of the FSV maps could not be pursued yet. The plausibility of the maps was instead assessed in terms of forest/ non-forest information by comparing them to free available but coarsely resoluted land cover datasets. For this purpose a multi-scale comparative assessment design with existing land cover products such as GLC 2000, GlobCover and MODIS VCF product was considered.

4.1 Sampling design

The sampling design has been based on the FAO *FRA2010 Sampling Design* [14] and the *Degree Confluence Project* [15]. Latitude and longitude intersects (confluence points) were used to create a systematic sampling grid/design with an area of 10 km x 10 km covered by each sample site (Figure 2). For each sampling grid, the forest stem volume maps and the corresponding land cover datasets were extracted and polygons were created. This enabled spatial analysis, such as area size comparisons, independent of the spatial resolution of the datasets being compared. Gaps in the FSV map due to lack of SAR data in particular over the central part of the study region complicates the assessment. (Figure 2).

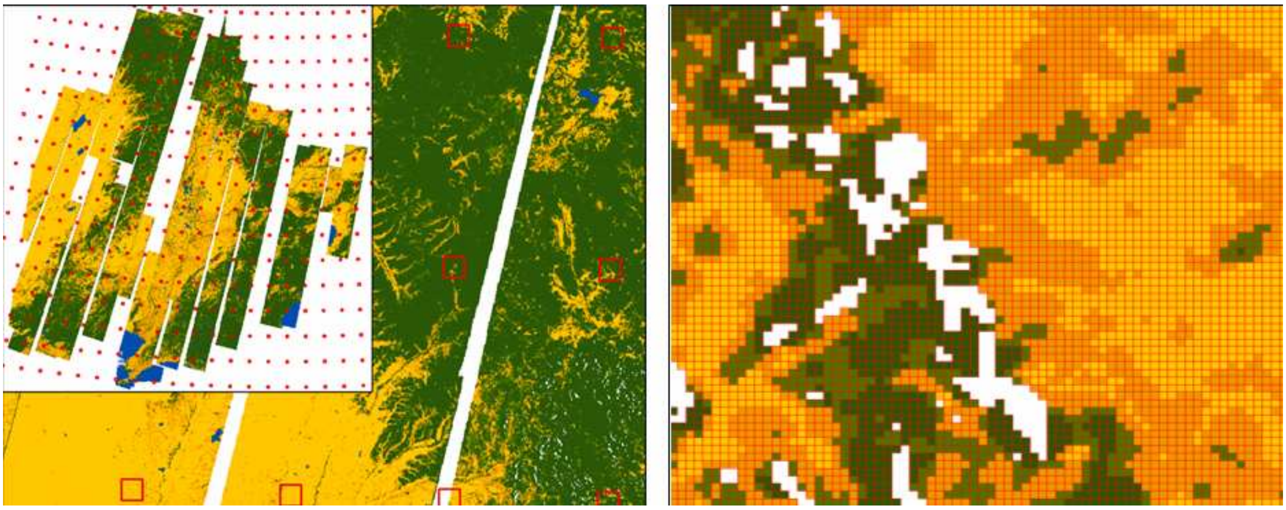

Fig. 2. Sample Plots with confluence centre points for Northeast China (left) and detail of a sample site with data gaps due to the radar geometry in mountainous areas (right)

4.2 Land cover products

Table 1 lists the different spatial and temporal resolution of each of the datasets used for the cross-comparison with the FSV map.

Table 1. The land cover datasets.

Product	Sensor	Resolution	Year
LC Classification	AVHRR	1 x 1 km	1981 - 94
LC Classification (GLC2000)	Spot	1 x 1 km	2000
Percent Tree Cover (MOD44B)	MODIS	0.5 x 0.5 km	2000 / 2005
GlobCover	MERIS	0.3 x 0.3 km	2004 - 2006

The AVHRR UMD land cover classification has been generated by the University of Maryland in 1998. Data from the AVHRR satellites acquired between 1981 and 1994 has been used to distinguish fourteen land cover classes [16]. The Global Land Cover 2000 (GLC2000) project is based on the VEGA 2000 dataset. This dataset consists of 14 months (1 Nov. 1999 – 31 Dec. 2000) of daily 1-km resolution satellite data acquired over the entire globe by the VEGETATION instrument on-board the SPOT 4 satellite [17]. The MODIS Vegetation Continuous Field Tree Cover product (VCF TreeCover) contains proportional estimates for the vegetation cover type woody vegetation for the years 2000 and 2005 [18,19]. The product is derived from monthly composites of the 500 m MODIS sensor onboard NASA's Terra satellite. All seven MODIS bands were used to calculate the percentage tree cover. The continuous classification scheme depicts heterogeneous areas better than traditional discrete classification schemes. While traditional classification schemes indicate where land cover types are concentrated, the VCF TreeCover product shows how much of forest cover exists on the land surface. GlobCover is an ESA initiative in cooperation with JRC, EEA, FAO, UNEP, GOFC-GOLD and IGBP. Based on ENVISAT MERIS 300m data global composites and land cover maps have been produced. The GlobCover service has been demonstrated over a period of 19 month (Dec. 2004 – Jun. 2006) for which a set of MERIS Full Resolution (FR) composites (bi-monthly and annual) and a Global Land Cover map are being produced [20].

4.3 Cross-comparison methods

Comparing different thematic maps such as the ERS-1/2 forest stem volume map (FSV map) and a coarse resolution land cover product, implies having to face a number of issues related to spatial resolution and nomenclature. A varying amount of thematic classes as well as different methods and algorithm used for the class assignation [21] and a different spatial scale of the maps lead to significant problems [22]. Different approaches have been published that can be utilized for a comparative assessment of the stem volume maps with the different coarser resolution land cover datasets. All approaches described below are based on the above described polygon based sampling design.

Approach 1: The cross-comparison assessment is conducted at the level of the single pixel of the FSV map. The affiliation of each of the FSV map pixel to the coarser resolution land cover map is analysed by using a geospatial union function on the basis of the vectorized raster datasets [23]. This allows an exact comparison of the high resolution FSV dataset with the coarser resolution land cover datasets without losing any thematic or spatial resolution. Problems occur when comparing the FSV map with ambiguous land cover classes, such as the *Globcover* class '*Mosaic vegetation (grassland/shrubland/forest) (50-70%) / cropland (20-50%)*', because an agreement of the ambiguous land cover class with several ERS classes is possible.

Approach 2: The cross-comparison assessment is conducted at the level of the coarse resolution single pixel of the land cover products. The distribution of the different FSV classes for each land cover class is analysed. Hence, the comparison of the FSV classes with the fuzzy described land cover classes (e.g. *Globcover* class: '*Mosaic vegetation (grassland/shrubland/forest) (50-70%) / cropland (20-50%)*') is possible. The method is not fully robust, because data gaps within the FSV map caused by the specific radar geometry in mountainous regions and due to gaps in the SAR data coverage prohibit the full coverage of the land cover pixels. Consequently, the analysed percentage distribution of the FSV classes is not complete. Hence, the results have to be considered as not clearly interpretable.

Approach 3 aggregates the FSV pixel to achieve the pixel resolution of the land cover product. The thematic aggregation of the FSV classes during the up-scaling process has to be done using assumptions, which implicates a high potential error [24,25]. Furthermore it is not possible to fully transfer the comparison assessment results of the aggregated FSV product to the original, high resolution FSV product. Due to the high uncertainty of the results, this approach was not considered for the cross-comparison analysis.

Because all methods described above are not fully robust when comparing the fuzzy described land cover classes and the stem volume classes of the FSV product, the comparative assessment of the FSV maps with the different land cover classes has so far been conducted on the basis of forest and non-forest classes only. Hence, a reclassification using the LCCS concept for the legend harmonization, suggested by UNEP and FAO [26,27] was accomplished (Table 2). According to the FAO *Forest Resources Assessment 2000*, China's stem volume averages 52 m^3/ha [28]. Hence, the FSV map classes 3 (50-80 m^3/ha) and 4 (> 80 m^3/ha) have been aggregated as forest (Table 2). Accordingly, method 1 and method 2 have been accomplished. The results of the two methods are statistics describing the correlation of the FSV product and the land cover products in terms of forest/ non-forest. The descriptive statistic analysis uses a 2D binning for the comparative assessment and results in correlation (difference/error) matrices.

Table 2. Legend harmonization of the stem volume maps and the land cover products into forest and non-forest classes only.

	Forest [Classes]	Non-Forest [Classes]	Class Description
Stem Volume Map	3,4	1,2,3	1 (0-20 m^3/ha) 2 (20-50 m^3/ha) 3 (50-80 m^3/ha) 4 (> 80 m^3/ha) 5 (Water)
GlobCover	0,11,12,14,15,20,30,40,130,134,140, 141,143,150,151,152,180,190,200,201, 202,203,210,220	50,60,70,90,91,92,100,110,120	[19]
GLC2000	1,2,3,4,5,6,9,10	11,12,13,14,16,17,18,19,20,21,22	[16]
AVHRR LCC	1,2,3,4,5,6,7	0,8,9,10,11,12,13	[15]

4.4 Results of the cross-comparison

The cross-comparison of the FSV map with the MODIS tree cover product (MOD44B) shows a very strong correlation of the distribution of the different FSV classes with the respective tree cover classes. The aggregated FSV forest class exhibits a coefficient of determination of 0.92 (Figure 3), which indicates the solidness of the FSV classes. However, a reliable statement of the accuracy of the aggregated FSV product is not possible.

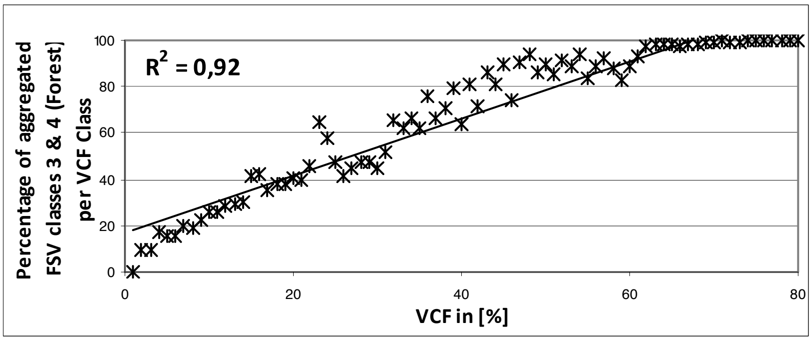

Fig. 3. Correlation between the aggregated FSV class and the MODIS tree cover classes.

The results of the cross-comparison of the FSV map and the remaining LC products on the basis of aggregated forest/ non-forest classes (Sec. 4.3), using a difference/error matrices is depicted in Table 3. The FSV product features a reasonable agreement with all LC products, though, due to the moderate thematic accuracy of the LC products [16,17,18,19,20] a strong uncertainty remains. The thematic information of the FSV map can be found within the LC products, which demonstrates the plausibility of the forest stem volume classification. Furthermore, areas where the FSV map and the LC products agree, the high resolution FSV product can provide information about the distribution of forest underneath the single coarse resolution LC pixel.

Table 3. Agreement between the forest stem volume map and the LC products on the basis of aggregated forest/ non-forest classes.

	Overall Accuracy	Cohen´s Kappa-Coefficient
FSV vs. GlobCover	0.74	0.49
FSV vs. GLC2000	0.79	0.59
FSV vs. AVHRR LCC	0.77	0.51

5. CONCLUSION

In this paper the generation and evaluation of large-area forest stem volume maps for Northeast and Southeast China using ERS-1/2 tandem coherence has been presented. Despite of an increasing theoretical understanding of coherence over forest in the last decades, the operational use of coherence in forest monitoring has been hindered due to the unpredictable variability of coherence caused by different meteorological and environmental conditions of image acquisition.

An automated method for forest stem volume retrieval has been developed. The algorithm uses a Interferometric Water Cloud Model and thematic information from the MODIS Vegetation Continuous Field (VCF) tree canopy cover product. The methodological development of this approach has been carried out at test sites in Siberia for which long-standing experience has been gathered in several studies and projects before and applied to a large dataset of ERS-1/2 tandem coherence images covering Northeast and Southeast China.

For an evaluation of the large-area forest stem volume maps in terms of forest/ non-forest information a cross-comparison scheme was developed, using a multi-scale comparative assessment design. Free available, but coarsely resoluted land cover datasets have been used for the cross-validation comparison. For Northeast China the agreement was above 70 % with all LC datasets. The reasonable agreement between the FSV product and the LC products highlight the high performance of the presented stem volume retrieval approach. Due to the unavailability of large-scale datasets of in-situ measurements, an accuracy assessment could not be accomplished yet.

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